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Studying the Problem Solving Behavior of Experts and Novices in Physics Via Computer-Based Problem-Analysis Environments *

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ABSTRACT

The design and architecture of two user-controlled, computer-based problem analysis environments in classical mechanics are discussed. In the expert-like environment, the user analyzes problems according to a hierarchical concept schema consistent with how experts analyze novel problems in physics. In the second environment, the user searches a large equation data-base utilizing novice-like, surface feature keywords in order to locate the appropriate equation(s) to use in solving a problem. Cognitive and pedagogical implications of the research are discussed.

Novices and experts store and use domain-specific knowledge in distinctly different manners. Recall experiments reveal that experts "chunk" information into related clusters thereby facilitating recall, whereas novices display no evidence of chunking (Chase & Simon, 1973; Egan & Schwartz, 1979; Ehrlich & Soloway, 1982; Larkin, 1979). In contrast to novices, expert physicists use forward strategies, fewer equations, and shorter procedures to solve problems (Simon & Simon, 1978). Novice physics students also find it difficult to separate an abstract plan for solving a problem from the actual solution process, stating instead the equations that they would use, whereas experts outline an approach based on fundamental physics principles (Chi, Feltovich & Glaser 1981).

We are currently investigating the consequences of imposing two types of constraints on experts and novices engaged in solving problems in a branch of physics called classical mechanics. By "constraints" we mean that novices and experts will be asked to use one of two different computer-based, menu-driven environments to analyze problems before solving them. With the first analyzer, the user is asked to categorize the problem under consideration according to a hierarchical concept schema consistent with that used by experts to analyze problems. With the second analyzer, the user is asked to categorize the problem according to surface features consistent with those used by novices to solve problems.

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DESCRIPTION OF COMPUTER-BASED ANALYSIS ENVIRONMENTS

Hierarchical Analyzer

The Hierarchical Analyzer was designed to be consistent with research observations on expert physics problem solving behavior. When faced with a novel problem in which there is no obvious course of action, expert physicists first consider which basic principles apply, and then plan a solution strategy based on these principles. Consistent with this observation, Chi, Feltovich and Glaser (1981) found that, when asked to classify problems according to similarity of solution, novices use the problems' surface features whereas experts use the physical principle or law underlying the problem as the classification criterion. These findings suggest that an expert's knowledge-store can be described as a dense network containing clusters of related information with a hierarchical structure in which fundamental concepts occupy the top levels of the hierarchy, ancillary concepts occupy the middle portions, and domain-related facts and equations occupy the bottom levels of the hierarchy.

Two additional studies influenced the design of the Hierarchical Analyzer. Heller and Reif (1984) trained physics novices to generate a problem analysis called a "theoretical problem description." Force problems in classical mechanics were described in terms of concepts, principles and heuristics. When novices were induced to follow such descriptions, they improved substantially in their ability to construct problem solutions. Control novices, who received good grades in a classical mechanics course, were not able to generate appropriate descriptions of fairly routine problems. In a similar vein, Eylon and Reif (1984) investigated the effectiveness of imposing a hierarchical organization on the performance of different tasks in the domain of physics. They found that subjects who had received a particular physics argument organized in hierarchical form performed various recall and problem solving tasks better than subjects who had received the same argument non-hierarchically.

The Hierarchical Analyzer was designed to guide the user through a hierarchical analysis of a problem in terms of both concepts and heuristics. The user categorizes problems in terms of those principles and heuristics that can be used to construct a solution to the problem. This categorization is carried out by making selections from a number of menus. On any given menu, the selection made leads to another menu which is more specific than the previous menu, and which contains further menu selections consistent with the selection made on the previous menu.

The structure of the Hierarchical Analyzer resembles a flat-top pyramid. At the top of the pyramid are the four most fundamental concepts into which we have chosen to partition elementary classical mechanics. These are (1) Newton's Second Law or Kinematics, (2) Angular Momentum, (3) Linear Momentum, and (4) Work and Energy. After the initial classification, the user proceeds to menus containing ancillary concepts and useful heuristics, which occupy the middle levels of the pyramid. The menus occupying the bottom levels of the pyramid become increasingly detailed until reaching the end result of the analysis -- an equation(s) that has been dynamically constructed in accordance with the classification scheme selected.

To understand the structure and functioning of the Hierarchical Analyzer, it is perhaps best to give an example. Consider the following problem:

A small block of mass M slides along a track having both curved and horizontal sections as shown. The track is frictionless. If the particle is released from rest at height h, what is its speed when it is on the horizontal section of the track?

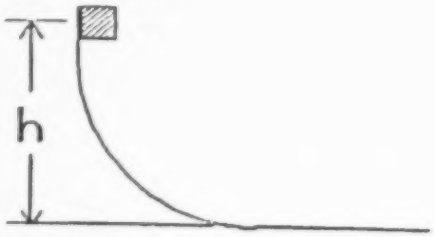

Figure 1 contains the series of menus and menu selections which appropriately analyze the problem (we have placed an asterisk next to the appropriate choice to facilitate discussions). Several features of Figure 1 should be noted. This problem can most easily be solved using work and energy principles, and thus menu item #4 is the appropriate selection. The second menu level is more specific and asks the user to describe the mechanical energy of the system. Selection #1, "Conservative system (Conservation of energy)," is the appropriate choice. Note the hints enclosed in parentheses to help the user decide which selection should be made. These hints guide the selection of choice (1) if conservative forces are present in the problem, or choice (2) if there are non-conservative forces present. At the third menu level, heuristics enter the hierarchy with the request to classify the changes in mechanical energy by considering one body at a time at some initial and final state. For the problem at hand, the block starts out with potential energy and ends up with only kinetic energy, so Selection #3 is the correct one. The fourth menu level asks the user for further classification of the changes in kinetic energy; in this case there is only a change in translational kinetic energy. At the fifth menu level, the user is asked to specify the boundary conditions (or conditions at the beginning and end points). Menu levels six and seven parallel of levels four and five for potential energy. At menu level number eight, the user is asked to specify whether there is more than one body in the system; in this case, the answer is "No." At menu level nine, the user is presented with a statement describing the principle s/he selected at the first menu level, and a statement about how this basic principle applies to the particular case at hand by elaborating on the restrictions imposed by the user's specific selections.

Note that the Analyzer does not provide the answer to a problem; it is a tool to aid the user in analyzing the problem. The user still must generate the equation that is the answer. For Problem #1, the user would have to perform some algebraic manipulations to obtain the correct answer, namely, $v=\sqrt{2gh}$. If the user has made an inappropriate selection at any menu level during the analysis, the end result would be an equation(s) that is consistent with the classification scheme selected, but inappropriate for use in solving the problem.

Three other features of the Analyzer should be noted. The "prompt line" at the bottom of menu levels 1-8 allow the user to choose options such as backing up to the previous menu in order to change a selection, entering a glossary to look up the definition of a term, or listing the menu selections made thus far. Second, if a problem lends itself to two different correct analyses, the Analyzer will allow for these two correct paths through the menu network. Finally, the user is given three choices at the final menu: 1) the problem is solved if the equation(s) given at the penultimate menu level are appropriate, 2) the user may review the equation(s) given in the penultimate menu level, or 3) if the problem being analyzed requires that two (or more)

FIGURE 1

Hierarchical Analyzer Menus & Choices

1

Which principle applies to this part of the problem solution?

1. Newton's Second Law or Kinematics
2. Angular Momentum
3. Linear Momentum
*4. Work and Energy

Please enter your selection: __

(B)ackup (M)ain menu (G)lossary (Q)uit (L)ist selections

2

Describe the system in terms of its mechanical energy

*1. Conservative system (conservation of energy)
2. Non-conservative system (work-energy exchange)

Please enter your selection: __

(B)ackup (M)ain menu (G)lossary (Q)uit (L)ist selections

3

Describe the changes in mechanical energy. Consider only the energy of one body at some initial and final state

1. Change in kinetic energy
2. Change in potential energy
*3. Change in potential and kinetic energies

Please enter your selection: __

(B)ackup (M)ain menu (G)lossary (Q)uit (L)ist selections

4

Describe the changes in kinetic energy

*1. Change in translational kinetic energy
2. Change in rotational kinetic energy
3. Change in translational and rotational kinetic energies

Please enter your selection: __

(B)ackup (M)ain menu (G)lossary (Q)uit (L)ist selections

5

Describe the boundary conditions

*1. No initial translational kinetic energy
2. No final translational kinetic energy
3. Initial and final translational kinetic energies

Please enter your selection: __

(B)ackup (M)ain menu (G)lossary (Q)uit (L)ist selections

6

Describe the changes in potential energy

*1. Changes in gravitational potential energy
2. Changes in spring potential energy
3. Changes in gravitational and spring potential energies

Please enter your selection: __

(B)ackup (M)ain menu (G)lossary (Q)uit (L)ist selections

7

Describe the boundary conditions

1. No initial gravitational potential energy
*2. No final gravitational potential energy
3. Initial and final gravitational potential energy

Please enter your selection: __

(B)ackup (M)ain menu (G)lossary (Q)uit (L)ist selections

8

Is there another body in the system which has not been examined?

1. Yes
*2. No

Please enter your selection: __

(B)ackup (M)ain menu (G)lossary (Q)uit (L)ist selections

9

The Work-Energy Theorem states that the work done on the system by all non-conservative forces is equal to the change in the mechanical energy of the system:

$$W_{nc} = E_f - E_i$$

According to your selections,

$W_{nc} = 0$ (Conservative system: mechanical energy conserved)

$E_f = (1/2\ mv^2)_{ff}$

$E_i = (mgy)_{ii}$

Please press any key to continue

10

*** Work and Energy ***

1. Problem solved
2. Return to Main Menu to continue solution
3. Review previous solution screens

Please enter your selection: __

different principles be applied in the analysis, the user may return to the main menu and continue. This third choice would be necessary if, for example, the block of the problem above suffered a totally inelastic collision with a second, stationary block on the level part of the track; in this case, the user would need to make a second path through the Analyzer choosing Linear Momentum at the first menu for the collision portion of the solution.

Formula-Centered Analyzer

The Formula-Centered Analyzer is intended to emulate the problem solving processes of novice physics students. It is flexible in that it could be used in a number of different ways by a number of different novices. Novices solving problems in physics tend to focus on finding the appropriate equation which can be manipulated to yield an answer. The most amusing evidence of this behavior is a typical "formula sheet" that students are allowed to take to physics exams -- it consists of a solid mosaic of equations. Further, novices appear to cue on a problem's surface features in deciding what equation to use. Surface feature cues take one of three possible forms: 1) problem types, such as "inclined plane" and "falling bodies," 2) variable names, such as "mass" and "velocity," and 3) physics terms, such as "potential energy" and "momentum."

The Formula-Centered Analyzer is a computer-based, sortable data-base made up of the equations in the first fourteen chapters of the commonly used classical mechanics text, Fundamentals of Physics by Halliday and Resnick (1974). This equation data-base contains over 150 equations, which the user can reduce by performing sequential sorts according to any one of three criteria: Variable Name, Problem Type or Physics Term. For example, for the problem above, the user may first choose to perform a sort according to the Variable Name "height," producing a list of those equations containing the variable "h." The user can then browse through the reduced equation list, or perform another sort. If the user chooses to perform another sort, for example using the Problem Type "sliding bodies," the data-base would be further reduced. After a few sorts, the number of equations would be reduced to a small, manageable number with specific properties, from which the user can select the one or two needed to solve the problem.

COGNITIVE AND PEDAGOGICAL RAMIFICATIONS

The two Analyzers described above are currently being used to study the problem solving behavior of both novices and experts. In particular, we are interested in whether or not novices exhibit distinctly different patterns of problem categorization and problem solving proficiency after prolonged use of one of the two Analyzers. With experts, we are interested in observing how they use both Analyzers; for example, do they use the Formula-Centered Analyzer as a hierarchical structure by only sorting according to Physics Term, or do they judiciously pick just the right combination of sorts to make their path to the desired equation as efficient as possible?

Although much is known about how experts and novices store domain-specific knowledge, and about how they solve problems, relatively little is known about the process of making the transition from novice to expert. We know that it

takes considerable time to become an expert, and that solving large numbers of problems is a necessary, but not sufficient condition for expertise. The work discussed in this paper is intended to address issues concerning the process of becoming an expert.

From a cognitive perspective, it is important to begin to understand how the transition from novice to expert occurs, and how it can be facilitated. Observing novices' and experts' problem solving behavior in the problem-analysis environments described above may shed some light on such questions as: 1) where along the expert-novice continuum a particular individual lies, and 2) the ability to ascertain a novice's "expert potential," or potential for becoming an expert in the domain in question. For example, the type of sort that an individual chooses to make when using the Formula-Centered Analyzer (that is, whether to sort only by variable name, or by physics term) may provide a good measure of an individual's position along the expert-novice continuum. More quantitative measures may be found in the length of time it takes a novice to adapt to the Hierarchical Analyzer, the number of specious analyses made and the ability to recognize a specious analysis.

From a pedagogical standpoint, the Hierarchical Analyzer could also provide the novice with the opportunity to actively participate in problem solving activities, while at the same time assimilating expert-like heuristics and methods for analyzing problems. In today's educational scenario, novices do not have an opportunity to observe experts engaged in problem solving activities for any prolonged period of time. When an expert physicist solves a problem for a novice, the solution is chosen for its clarity or elegance and often bears little resemblance to the process that the physicist used to solve the problem. The Hierarchical Analyzer could be a cost-effective tool for providing novices with real expert-like problem solving experiences.

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